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Overview of miniature CMOS camera and its applications

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Dedicated to Prof T Asakura

Miniature CMOS (complementary metal oxide semiconductor) cameras are applied to smart phones, medical devices, and automobiles. The paper overviews the operation and structure of CMOS image sensor. The paper also presents the wafer level camera module including CMOS image sensor and wafer level lens.

Keywords: CMOS image sensor, Wafer level lens, Wafer level camera.

1 Introduction

A camera is essentially to function as the eye, to capture the image of an object viewed by a person. The eye has a lens to form an image, and retina to capture the formed image. Similarly, a camera has a lens to form an image, and a photosensitive part to capture the formed image. A comparison of the eye and a camera is illustrated in Fig. 1.

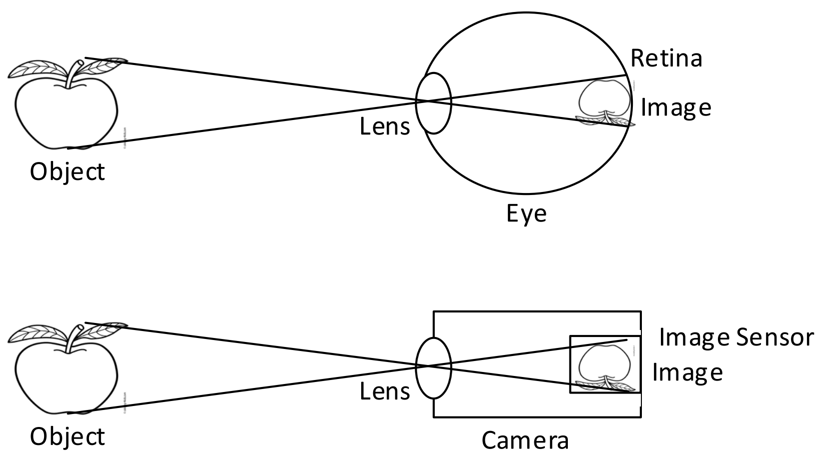

Fig. 1. Comparison of eye and camera.

A camera is superior than the eye in the sense of function that it can store the image captured in the memory, while the eye is refreshed at all time. In an old fashion camera, the image is captured by a photographic film, and the film functions as an analog memory as well. In today's cameras, the image is detected and captured by an image sensor. The image sensor typically produces a digital image signal that can be displayed on an electronic display or can be stored in storage or memory.

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The retina includes about 7 million photoreceptor cone cells and 150 million photoreceptor rod cells. Cone cells are sensitive to bright light and colors, while rod cells are sensitive to dim light and not sensitive to colors. Currently, a commercial CMOS image sensor has 24 millions of pixels. Although the number of pixels of a CMOS image sensor is about 1/6 of the number of rod cells of the eye, the pixel size of the CMOS image sensor is about 0.9 µm, while the diameter of cone sell is about 0.4-5 µm, and the diameter of rod cell is about 2 µm. A CMOS image sensor having 111 million pixels has been made [1].

2 Principle of CMOS Image Sensor

An image sensor consists of an array or pixels. The main function of image sensor is to convert the photons captured in a pixel to an electronic signal. Each photon will generate an electron in the pixel. In a time period known as exposure time, the electrons generated by the photons falling into a pixel are accumulated. The collected electrons generate an electronic signal of the pixel. The magnitude of the electronic signal is proportional to the number of photons, which is also proportional to the intensity of light falling on the pixel.

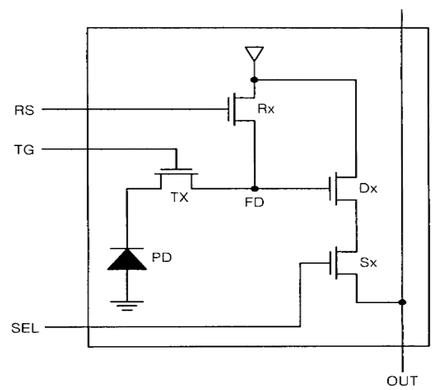

Fig. 2. Pixel of CMOS image sensor having four transistors.

The operation of CMOS image sensor can be explained referring to Fig 2. Photons falling on a pixel are converted to accumulated electrons at the photodiode (PD). When the transfer gate (TX) is turned on by providing “on” TG signal, electrons from the photodiode are transferred to the floating diffusion region (FD). The source follower transistor or drive transistor (DX) detects the voltage produced by the transferred electrons. The voltage controls the current passing through the source follower transistor. The current is outputted from the pixel. The output current is switched on and off by the row select transistor (SX) by providing “on” or “off” SEL signal. The operation also involves another column select operation that is not shown in Fig 2. Figure 2 is under assumption that column select is "on". After the current is outputted, the reset transistor (RX) is turned on by providing “on” RS signal, the electrons in FD are released and FD is emptied. The operation is repeated for the next frame.

The structure of a CMOS image sensor is depicted in Fig 3. The pixel is formed in a silicon wafer. The base silicon wafer is P-doped (p-Si). The photo diode (PD) is formed by N-doping the silicon (n region). The n region of photo diode is surrounded by stronger P-doped silicon (p+ region) forming a PN junction in the photo diode. Under light illumination, electron-hole pairs are generated. The generated electrons are accumulated in the n region of the photodiode, while the generated holes are collected by the ground.

The floating diffusion (FD) is formed by doping the silicon with stronger N-doping (n+ region). When the transfer gate (TX) is on, a channel between the photodiode and floating diffusion is opened for the electrons. The potential at floating diffusion (n+ region) is lower than the potential at the photo diode (n region) for electrons, so electrons are transferred from the photo diode to the floating diffusion. Ideally, all electrons in the photo diode are transferred to the floating diffusion.

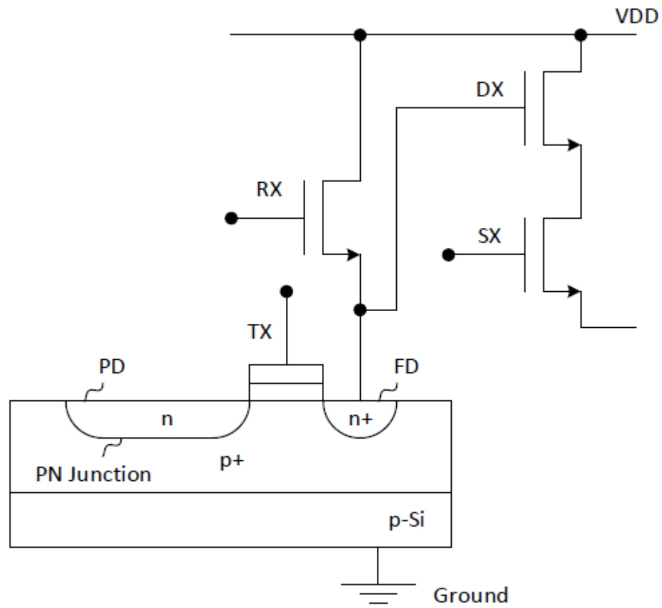

Fig 3. Structure of pixel of CMOS image sensor having four transistors.

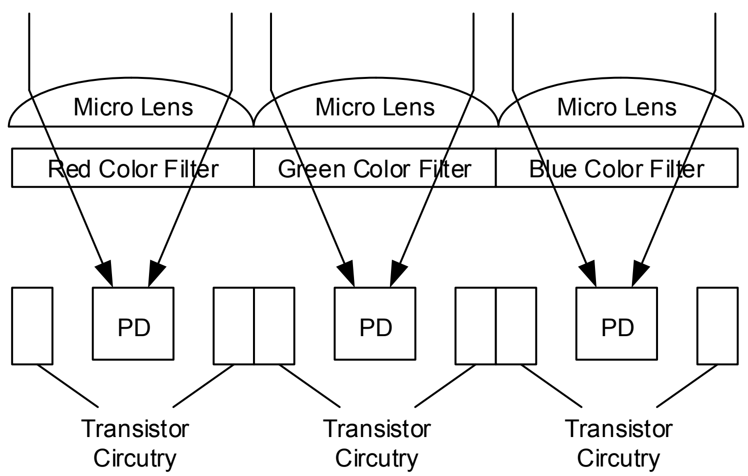

Fig 4. Structure of pixel covered by micro lens and color filter.

N- doping is provided by doping phosphorus, arsenic, or antimony that have five outer electrons, and P- doping is provided by doping boron, aluminum, or gallium that have three outer electrons. Silicon has four outer electrons. Reset transistor (RX), source follower transistor or driver transistor (DX), select transistor (SX), and other transistors required for the circuit can be formed in the same silicon wafer by proper doping.

To maximize the light collected in a pixel, each pixel is covered by a micro lens, as schematically illustrated in Fig 4. The micro lens is larger than the photo diode. A photo diode and other transistor circuitry, e.g., RX, DX, SX transistors, are covered under a micro lens. Currently, 0.9 µm pixel size is available. In this case, the diameter of the micro lens is 0.9µm. To detect a color image, each pixel is covered by a color filter as also illustrated in Fig 4. The color filter can be red (R), green (G), or blue (B) color filter to detect R, G, and B image signals. The detected R, G, and B image signals can be provided to a display to display a full color image.

3 Wafer Level Lens and Wafer Level Camera

A silicon wafer having a circular shape and diameter of 300 mm (12 inch) with a thickness 775 µm is available. A CMOS image sensor die has approximately 1-10 mm size depending on the pixel number and pixel size. Accordingly, a number of CMOS dies can be made in a wafer. Conventionally, a CMOS image sensor is singulated from a wafer. The singulated CMOS image sensor is then individually packaged. The individually packed CMOS image sensor is further packaged with a lens system to form a camera or camera module.

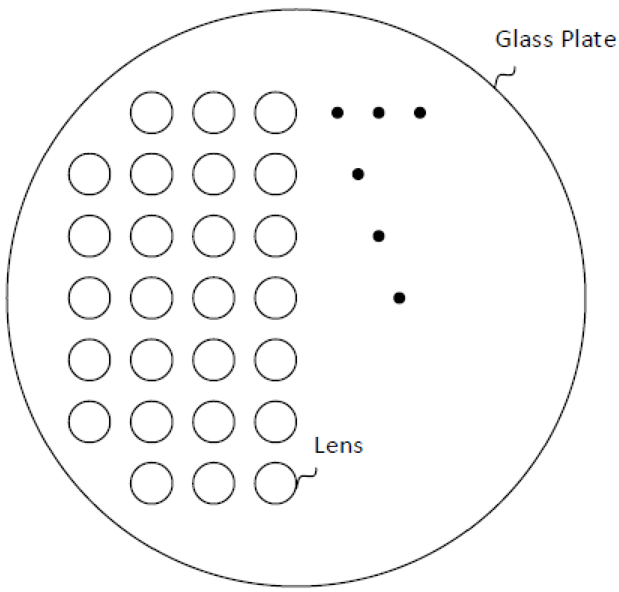

Fig 5. Schematic diagram of a lens plate having a number of lenses.

A number of lenses can also be made on a glass plate having the same shape and size as a silicon wafer. The lenses are made at the same time using a mold or molds on the glass plate. The glass plate with a number of lenses on it is known as a lens plate as shown schematically in Fig 5. Multiple lens plates may be stacked together to form a lens plate wafer-unit. A lens manufactured in this way is known as a wafer level lens.

In a wafer level process, the lens plate wafer-unit includes lens plates and spacer wafers. The lens plate wafer-unit is placed on a CMOS image sensor wafer forming a number of camera units. The camera units are in the form of stack of wafers as shown schematically in Fig 6. The formed camera unit is then singulated from the stack of wafers and individually packaged as a camera module. The singulated camera made by this process is known as wafer level camera.

A camera module is schematically depicted in Fig 7. The camera module normally includes an image sensor, a first spacer on the image sensor, a first lens plate on the first spacer, a second spacer on the first lens plate, and a second lens plate on the second spacer.

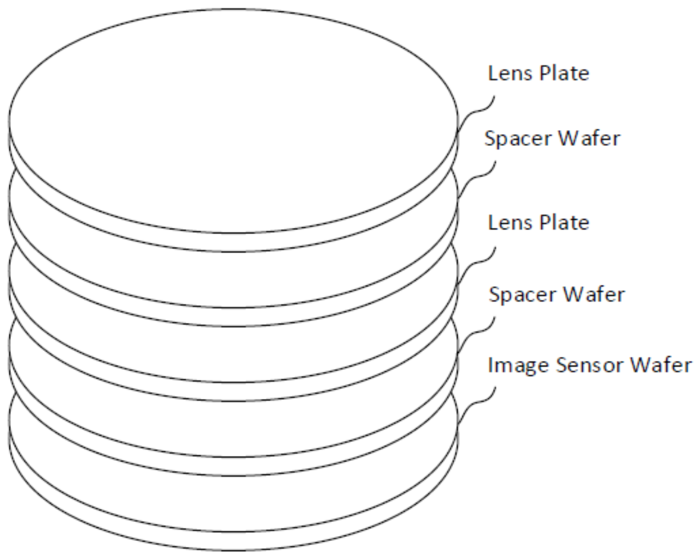

Fig. 6. Schematic diagram of a stack of wafers forming a number of wafer level cameras.

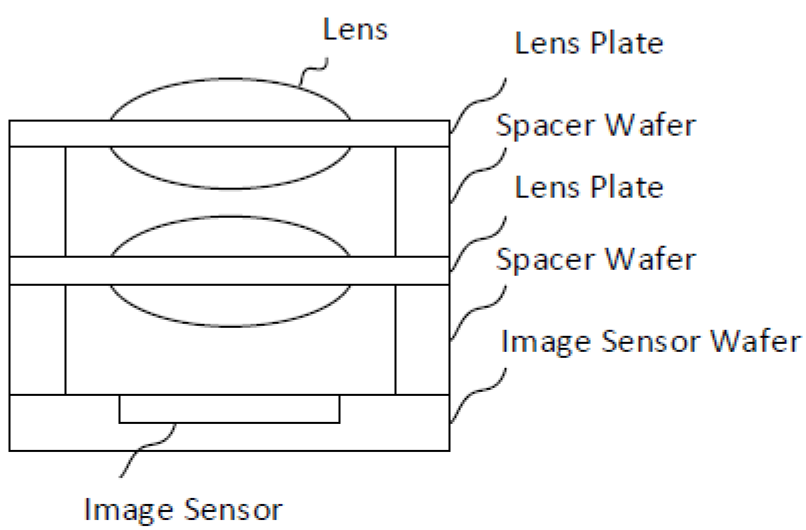

Fig 7. Schematic diagram of a camera module.

4 Applications

(i) *Smart phone*

A typical application of CMOS image sensor is camera module for smart phone as illustrated in Fig 8.

(ii) *Capsule endoscope*

Recently, very small CMOS image sensors are available, for example, a CMOS image sensor die of 0.575×0.575 mm^2 with 40,000 pixels made by OmniVision [2], so small size camera modules can be made.

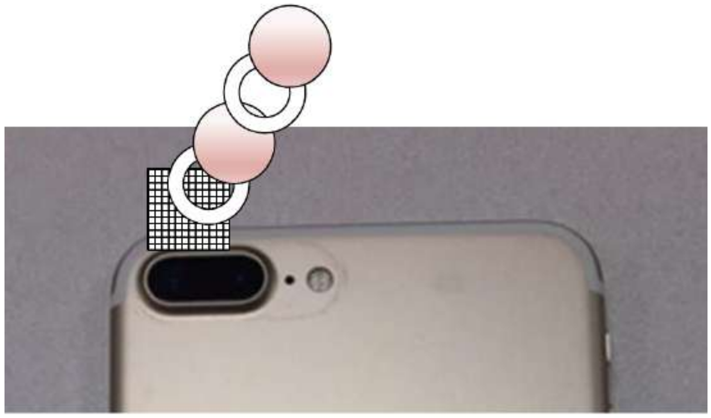

Fig 8. Illustration of CMOS camera module including image sensor, first spacer, first wafer level lens, second spacer, and second wafer level lens in smart phone.

The small size camera module can be included in an inserting-type endoscope or a swallowable capsule endoscope as illustrated in Fig. 9. A capsule endoscope can be swallowed, and while it travels in the body it takes pictures along the digestive tract.

Fig. 9. Illustration of capsule endoscope in a hand.

Capsule endoscopy [3] is a procedure that uses a tiny wireless camera to take pictures of the digestive tract. A capsule endoscopy camera sits inside a vitamin-size capsule the patient swallows. As the capsule travels through the patient's digestive tract, the camera takes thousands of pictures that are transmitted to a recorder the patient wear on a belt around the patient's waist.

In another approach, no wireless transmission of data is used. The pictures taken are stored in the capsule endoscope until the capsule endoscope exits from the patient's body. The stored data is retrieved after the capsule endoscope is collected. In both approaches, the capsule endoscope is equipped with LED light source for illumination inside the patient's body.

Capsule endoscopy helps doctors see inside the patient's small intestine — an area that is not easily reached with more-traditional endoscopy procedures. Traditional endoscopy involves passing a long, flexible tube equipped with a video camera down the throat or through the rectum.

(iii) *Automobile*

Currently, CMOS cameras are also applied to automobiles. Almost every car now is equi-pped with rear view cameras to see the rear view when the car is backed up. Many more image sensors are required as multiple sensors for ADAS (advanced driver assistance system) and future self-driving cars. Figure 10 shows CMOS image sensors required for ADAS [4].

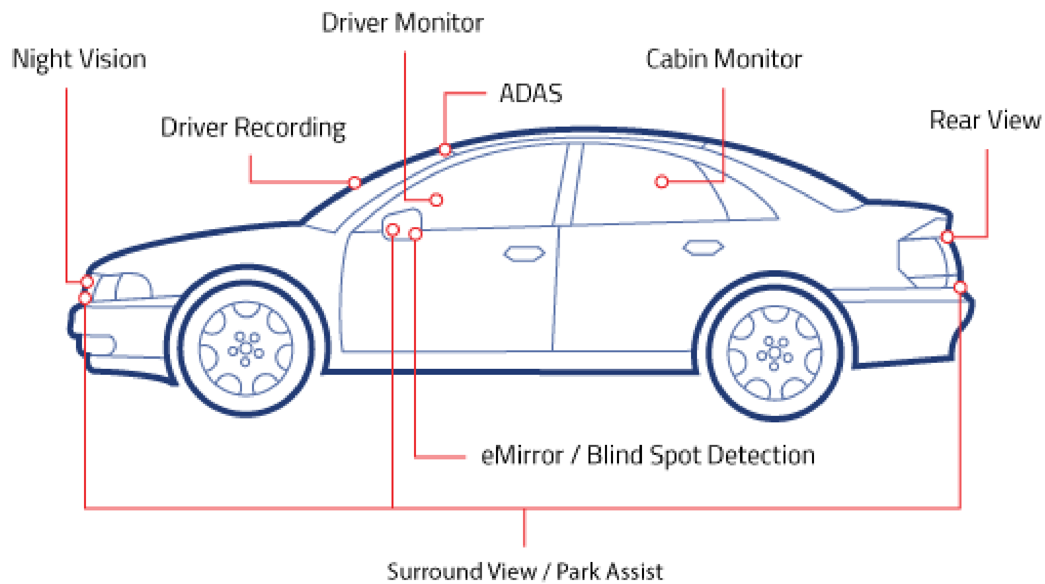

Fig 10. Image sensors required for ADAS (advanced driver assistance system) [4].

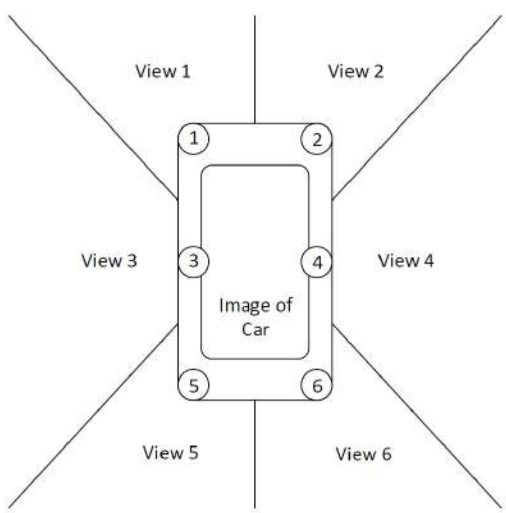

Fig. 11. Synthesized bird's eye view for assisting parking.

It is interesting to note that individual surrounding views captured by six cameras on the side of the car (see Surrounding View/Park Assist in Fig 10), can be synthesized into a single bird's eye view [5] using a special algorithm. Six cameras capture six views. The six views first are corrected for tilt view and then properly stitched together. The image of the car is added at the center to synthesize a bird's eye view as shown in Fig 11. Thus the driver of the car can see a bird's eye view of his car for assisting parking.

Artificial intelligence is taking the automobile industry by storm while all the major automobile players are utilizing their resources and technology to come up with the best. When artificial intelligence is applied to the technology within an automobile, it would recognize the environment and evaluate the contextual implications when it moves or faces any hurdles.

Machine learning is often referred to as a subset of artificial intelligence. It is a field of computer science that data based computational techniques create an ability for machine to learn without an explicitly programmed algorithm. Deep learning is a class of machine learning that uses a cascade of multiple layers of nonlinear processing units for feature extraction and transformation. It is a kind of neural networks or neural computing.

The machine learning algorithms may track vehicle speed, location, destination and even preferences to provide and transmit the right information. In autonomous driving and in most of the functions of ADAS, artificial intelligence provides vehicles with the so-called artificial vision [6]. The ability of vehicles to identify various objects, scenes and activities in unrestricted environments is one of the key technologies in the automotive industry. The artificial vision of the vehicle may be provided by a plethora of cameras. The machine learning algorithms are based on object detection and the recognition of sophisticated patterns. The computerized vision constantly analyzes the environment. The images are then analyzed and the nature of the objects is classified by artificial intelligence. The goal is to perceive the environment around at 360 degrees through various sensors including CMOS cameras.

Conclusion

As semiconductor technology progresses, image sensors having pixels that are approaching human's eye cell in size and number are becoming available. Miniature cameras including CMOS image sensors and small lenses are commercially available. These miniature CMOS cameras are applied to smart phones and swallowable capsule endoscopes. Recently, cars are equipped with miniature CMOS image sensors for the driver seeing the environment, for example when the car is backed up. In future the image sensors will be combined with artificial intelligence in automotive industry.

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